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Measurement of dynamic comfort in cycling using wireless acceleration sensors

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Abstract

Comfort in cycling is related to the level of vibration of the bicycle: more vibration results in less comfort for the rider. In this study, the level of vibration is measured in real time using wireless inertial acceleration sensors mounted at four places on the bike: front wheel axel, rear wheel axel, stem and seatpost. In this way, we measure both the input and output of the frame and fork, and consequently establish the transfer function of the frame and front fork. Besides the transfer of vibrations through the frame, we also investigate the input to the frame and fork. Moreover, we determine the effect of the road surface, speed, wheels and tire pressure on the vibrations induced to the frame and fork.
Our analysis shows that road surface, speed and the tire pressure have a significant influence on the induced vibrations. On the contrary different wheelsets have no significant influence. Additionally, the vibrations propagate through the frame within a duration of 5 ms.

Keywords: Cycling; comfort; vibrations; accelerometer; wireless

1. Introduction

Many cyclists ride their bikes for hours during a single trip. Comfort during cycling is therefore important for both recreational riders and professional riders. Vibrations are an important source of discomfort. Vibrations from road irregularities are transferred through the bike to the cyclist. ‘Stronger’ vibrations will lead to a less comfortable ride. There are numerous options to dampen these vibrations, for example deflating the tires. But a frame with less vertical stiffness would in theory also result in fewer vibrations.

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The first two points should be categorized as '*static comfort*' according to Champoux et al [1]. In this study the focus will be on point 3: '*dynamic comfort'*. Vibrations are oscillatory motions, which can occur in different forms. The magnitude of the vibrations can be measured as a displacement, velocity or acceleration. Most common is to measure the acceleration, which will also be used in this research. Analyzing vibrations can be done in multiple domains; in most cases the frequency domain is more useful than the time domain. The frequency domain reveals harmonic signals which cannot be seen in the time domain. The root mean square (RMS) value can be used as an indicator of the severity of the vibrations. This RMS value can be calculated both from the data in the frequency domain and the data in the time domain. When the vibrations consist of shocks or are non-stationary the root mean quad (RMQ) is more useful [2].

The Eigen frequencies of most organs and limbs are in the region between 0.5 Hz and 10 Hz [3]. Vibrations with strong frequency components in this region will decrease the comfort of the cyclist. Frequencies above 10Hz are of less importance.

For measuring vibrations, recently developed MEMS (Micro Electro-Mechanical Systems) accelerometers represent a promising technology. These MEMS accelerometers are small and cheap, and many of them feature digital outputs, multiple axes and low power consumption. These properties make them ideal to measure movement in sports.

2. Method

The hardware used consists of four devices:

1. Inertial sensors to measure the vibrations.
2. Mounting brackets to attach these sensors to the bike
3. A GPS receiver
4. The bike

The inertial sensors were the ProMove2 wireless nodes from Inertia Technology [4]. These sensors feature 8 degrees of freedom of motion information, a dedicated microcontroller and a separate System-on-Chip (SoC) solution for low-power wireless networking. The network of sensor nodes is connected to a notebook by the FastGateway. On the notebook the ProMove GUI software displays and logs all acquired data for future processing.

The GPS receiver is a Garmin Edge 705. The receiver is configured to store all received data every second. Automatic pausing is turned off, so the files are continuous in time.

The primary bike during testing was a Sensa Lombardia road bike. The secondary bike used during the tests is a Simplon Gravity mountainbike. The major specifications of these bikes are printed in table 1.

Table 1. Specifications of the bikes used during testing

Frame:	Size:	Fork:	Tires:	Width:
Sensa Lombardia	55 cm	Easton EC90 SL	Vredestein Volante	23 mm
Simplon Gravity	57 cm	Manitou R7	Schwalbe Racing Ralph	2.25 inch

2.1. Placement of the sensors

Four sensors were attached to the bike. Two sensors were mounted to the quick releases of the front and rear wheel. The other two sensors were placed on the stem and the seatpost. This way the sensors measure the input vibrations from the road surface and the vibrations transferred to the cyclist by the frame and fork.

2.2. Data processing

The data processing is done in Matlab. The processing of the inertial nodes starts with filling the packets lost in the wireless communication. Since some inertial nodes are mounted tilted, the outputs have to be corrected for this tilt. From the raw acceleration data the tilt of each node is calculated. The tilt is used to generate a rotation matrix. The raw data is multiplied with the rotation matrix to correct the data for the tilt of the inertial nodes. The next processing step is filtering the acceleration data. A high pass filter is applied to the data to remove the gravity component in the accelerations. The final processing step for the accelerometer data is low pass filtering the accelerometer data.

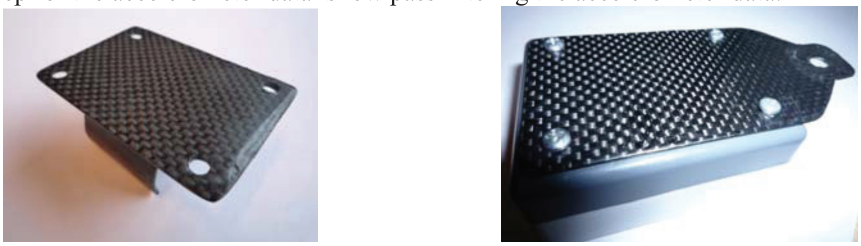

Fig. 1.(a) Carbon fiber mounting bracket for the sensors to the seatpost of stem; (b) Bracket for mounting the sensor to the quick release or seatpost clamp. The sensor lays up-side-down in the picture

2.3. Measurements

All measurements described below have been done on short laps consisting of multiple types of pavement. Three specific experiments have been done, in each of the three experiments one of the variables has been changed while keeping the others constant. In the first test the tire pressure has been varied. Four pressure levels have been tested: 5, 6, 7 and 8 bar. The second test was done on the mountain bike; in this test the speed was varied. The first 3 laps were ridden with a cruise speed of 18 km/h, the following laps with 25km/h and 32 km/h, respectively. During all 9 laps the Manitou suspension fork was locked. Three additional laps were ridden at 25 km/h, but with the fork unlocked. During the third experiment different wheelsets were used. Four mid-class wheelsets, which were expected to have the largest differences in comfort (16 spokes vs. 32 spokes, low vs. medium profile rims, etc) were selected. On all 4 tested wheelsets the same Continental 4-season tires were mounted and inflated to a pressure of 7 bar.

3. Results

After a couple of initial tests the accelerometers were configured to measure acceleration at their maximum range of ±6 g. Hitting a minor pothole results in an acceleration of more than 6 g, so the sensor clips some times. In figure 2 top part, acceleration data in the time domain is shown. This data has been corrected for tilt and filtered. The bottom part of figure 2 shows the speed during the 3 laps, where each lap can be easily identified, due to the stop periods. The impact of different road types is also visible, for example the difference between the smooth asphalt and the small cobbles is very high. Riding on smooth asphalt happens just before 15:05. The transition from asphalt to the cobbles is not flat, but there is a small bump in the road. The result of this small bump is clipping sensors at this point.

3.1. Tire pressure experiments

Table 2 shows the results of the experiments with the four different tire pressures. The data shows that a lower tire pressure increases the comfort. Of course there is also a down side to lowering the tire pressure: the chance of having a 'snake bite' flat increases and the rolling resistance increases too.

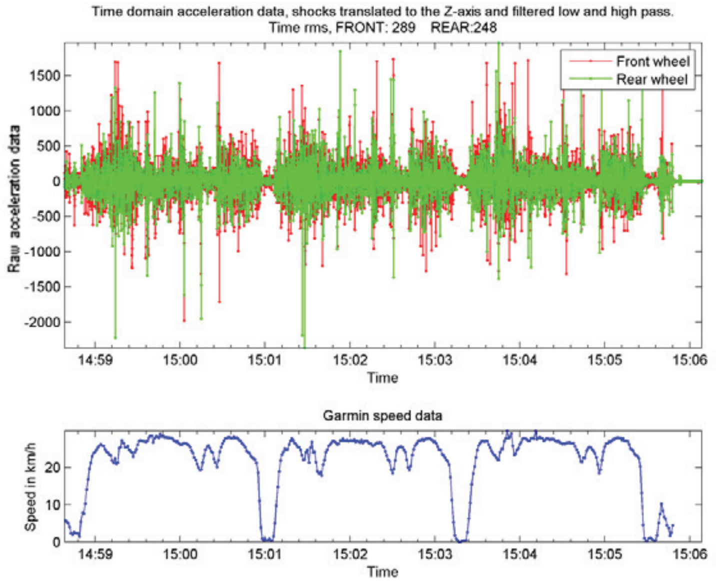

Fig. 2. Time domain acceleration data and GPS signal of a test ride with 5 bar pressure in the tires

Table 2. RMS values of the accelerations in the time domain for different tire pressures

Pressure:	Front wheel (m/s^2):	Rear wheel (m/s^2):
5 bar	11.6	9.9
6 bar	13.2	11.4
7 bar	14.7	12.4
8 bar	15.8	14.0

3.2. Speed experiments

The results of these tests on the mountain bike are listed in Table 3. The tire pressure was 2 bar in both front and rear tire. The relation between the speed and accelerations (in RMS) seems to be quite linear. These results underline the necessity to keep the speed as constant as possible in the other tests, since the speed has a large influence on the level of vibration.

When the fork is unlocked the acceleration on the front wheel are a lot larger. This was also expected since the front wheel can move more freely when the fork is not locked. The vibrations for the rear wheel did not change significantly.

Table 3. RMS values of the accelerations in the time domain for the different speeds and the fork locked and unlocked

Speed (km/h):	Fork suspension:	Front wheel (m/s^2):	Rear wheel (m/s^2):
18	Locked	4.5	4.5
25	Locked	6.7	6.3
32	Locked	9.5	8.2
25	Unlocked	7.8	6.5

3.3. Wheel experiment

Many cyclists believe that there is a big difference in comfort between different wheels. Even when the difference in rim height is only 7 mm (23 mm vs. 30 mm), there could be a large difference in comfort according to many cyclists. The results of the tests with multiple different wheels differed less than 6% in the RMS values. However within the 4 laps ridden with every wheelsets the difference are also up to 5%. Therefore, we have not experienced a significant difference in comfort between these mid-class wheels.

Table 4. RMS values of the accelerations in the time domain for different wheels

Wheelset:	Front wheel (m/s^2):	Rear wheel (m/s^2):
SRAM S27 Al Comp	15.3	14.5
Bontrager Race Lite Aero	16.3	15.4
Custom DT Swiss / Hope	15.1	15.0
Easton EA50 Aero	15.8	15.6

In Figure 3 Fourier transformed data from the four nodes is shown. The graphs show that the power from the vibrations decreases when they are transferred from the wheels to the stem and seatpost. The RMS and RMQ numbers confirm what can be seen in the graphs. By dividing the front wheel data with the data measured at the stem the damping ratio's are calculated. The result is shown in Figure 5. Some frequencies are damped more than other frequencies.

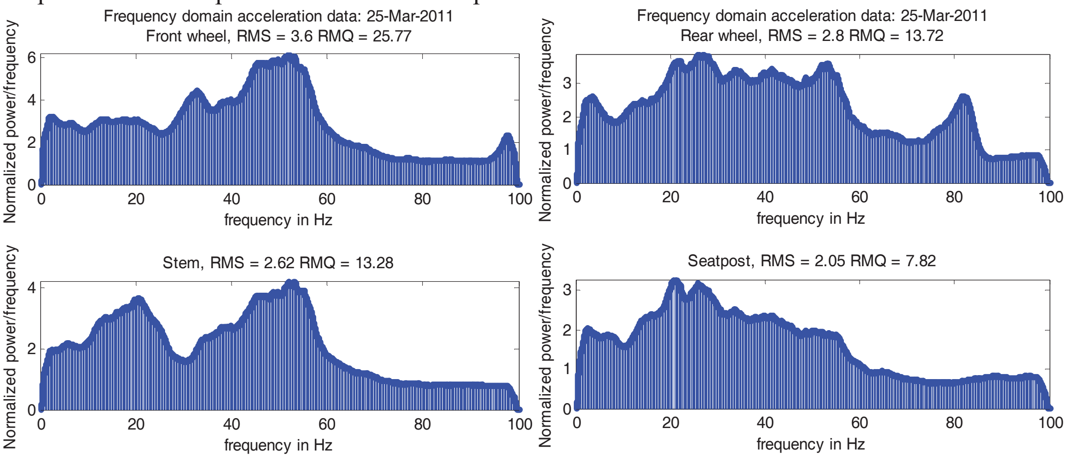

Fig. 3. Acceleration data of the 4 sensors transformed to the frequency domain

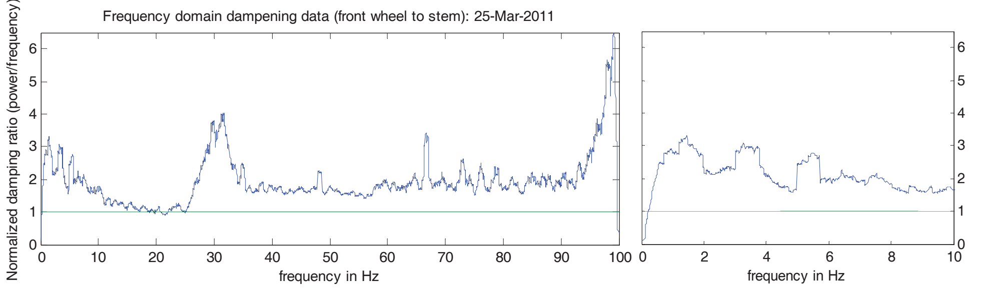

Fig. 4. Damping ratio's of the front wheel to the stem from the same test ride as in figure 3, with a close up of the 0 till 10 Hz region at the right

Cross-correlation is the measure of the similarity between two signals as a function of a time-lag. It is calculated with the following formula:

$$(f * g)[n] = \sum_{m=-\infty}^{\infty} f^*[m]\, g[m+n] \tag{1}$$

Since the rear wheel follows the front wheel, the sensor mounted at the rear wheel quick release should sense the same shocks as the sensor at the front wheel with some time delay. This time delay is calculated with cross-correlation. The correlation between the front wheel and the stem, plotted in Fig, shows there is no time delay between the shocks arriving at the quick release and the stem. In reality there will have to be a delay, since the shocks cannot travel with unlimited speed through the fork. However the shocks travel faster through the fork than the sampling time of the acceleration sensor (5 ms, corresponding to a sampling frequency of 200 Hz). In all other measurements this delay was also zero samples, i.e. less than 5 ms.

The time it takes for the shock to arrive at the rear wheel and seatposts was 24 samples during this test ride. Since the wheelbase of the bike is just over 1 meter, these 24 samples correspond with the average speed:

$$\frac{1}{\frac{1}{200}ms * 24\ samples} * 3.6 = 30\ km/h \tag{2}$$

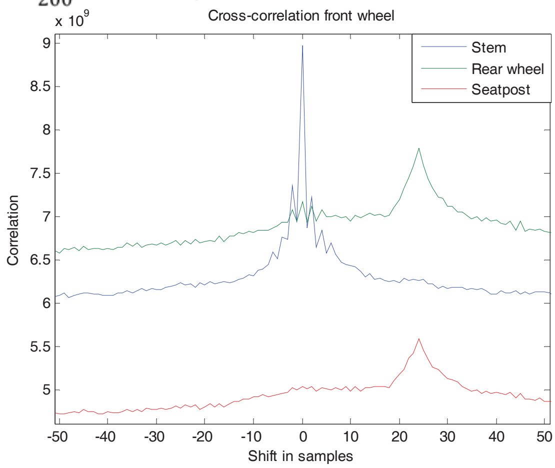

Fig. 5. Cross-correlation of front wheel with the stem, rear wheel and seatpost

4. Conclusion

Our experiments and analysis show what kind of vibrations can be expected on a road bike and what the influencing factors are:

- *Road surface* has a significant influence on the vibrations induced to the frame and fork.
- *Speed*. There is a strong relationship between the vibrations induced to the bike and the speed. With increasing speed, the vibrations increase approximately proportional.
- *Tire pressure*. An increase in tire pressure also increases the vibrations, thus reducing comfort. However the influence of tire pressure on the vibrations seems to be asymptotical.

The influence of several different wheelsets on the comfort was also tested. No significant differences are observed, contrary to the general belief that wheelsets have an important impact on comfort. The test person could neither feel any difference in comfort between the tested wheelsets.

The propagations of the vibrations from the front wheel quick release to the stem and from the rear wheel quick release to the seatpost is frequency dependent. Some frequencies are damped more than others, but for a proper analysis more experiments are needed. Our experiments show that the vibrations travel in less than the sampling time of 5 ms from the quick releases to the stem and the seatpost. The average speed can be calculated by calculating the cross-correlation of the front and rear measurements.

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